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Benefit-cost analysis of public safety investment on the example of the fixed speed enforcement cameras on the main roads of Estonia

Master's Thesis

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I recommend referring to the defense of the master's thesis

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Abstract

The objective of this paper is to calculate the benefit-cost ratio of Estonian speed camera program. The effectiveness of speed camera network is found by using before-and-after analysis with the comparison groups. The speed camera effectiveness is measured in the numbers of car accidents, fatalities and seriously injured persons. For a more accurate measurement, the general traffic safety trend and the regression-to-the-mean (RTM) effect are taken into account. The accident data is from the period 2003-2017 and is derived from Estonian Road Administration, Police and Border Guard Board, Estonian Traffic Insurance Fund, and the Ministry of Finance. The speed camera effects are monetized by using the cost of accidents, lives and injuries provided by the Traffic Insurance Fund and Koppel et al. (2005). The benefit-cost analysis shows that the speed camera program is beneficial for society because the benefit-cost ratio is 4.31. However, the revenue earned by the camera network is higher than the total cost of the program, and additional 977 703 euros is added to state revenue. The speed camera program could have saved 25 lives since its implementation.

Acknowledgment

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1. Introduction

Every year approximately 1.2 million people die, and 50 million get injured in traffic accidents around the world, and this trend is worsening if policymakers do not implement new measures for traffic safety (WHO 2015). In Estonia, for example, on average there were 74 fatalities and 1765 injuries resulting from car accidents in 2013 - 2017 (ERA 2018)[1].

The wrong driving speed is one of the leading causes of a car accident and a significant reason for death and injuries (WHO 2015). Many developed countries are implementing fixed speed camera networks as an extra speed calming measure on high-risk roads. The speed camera networks cause high public attention and are somewhat controversial as in some public opinion it is more of a state revenue filler than reasonable speed calming measure (Tang 2017). There are reports that some speed cameras placements have adverse effects on traffic safety and are itself the reason for car crashes (Elvik 1997). Several systems have even closed due to the proven adverse effects on traffic safety like Oxfordshire, West Midlands, Avon and Somerset, Wiltshire, Swindon and Northamptonshire in Great Britain (Tang 2017). There are many systems already in place in many countries. The central question for public decision makers is about the real measured effectiveness and the benefit-cost relationship of current systems and when it is feasible to expand or implement new speed cameras on road networks.

This thesis aims to find out the benefit-cost ratio of the current Estonian Speed Camera program on the main national roads. This thesis contributes to the existing literature as it is the economic feasibility view to the Estonian traffic safety subprogram. There are two limited effectiveness studies about the current Estonian automatic speed camera program (Draba 2012; Äär 2014), but no economic feasibility analysis has been done. The previous studies also analyzed only limited sections of the speed camera program and recommended looking at the effectiveness again when more data is available.

In the international literature, there are many studies about the effectiveness of the speed camera networks, but very little has been done about the economic feasibility. The existing economic evaluations are sketchy and straightforward. The benefit-cost analysis is more of a side product in the existing works and lacking a monetary view of the investment.

[1] ERA 2018: Traffic accident statistics: https://www.mnt.ee/et/ametist/statistika/liiklusonnetuste-statistika

In the literature review, this thesis first looks into the existing models that make economic evaluations for crime prevention in the assumption that this model can also be implemented for evaluating the traffic safety initiatives. Then the principles of the speed enforcement theory are explored to understand reasons for its implementation. The literature overview focuses on effective measurement methods and tactics of automated speed measurement in order to identify key indicators and the best way to evaluate available data.

Methodically this work is using the controlled before-and-after method for evaluating the effectiveness of current the Estonian speed camera network. Extra measures are taken to overcome the pitfalls of earlier studies like traffic trends and accidents regression to the mean (RTM). In the data section, the Estonian traffic safety program and camera network setup are introduced with available data of camera locations, accidents statistics, cost of crashes, injuries and deaths. The results and discussion chapter identifies the cost-effectiveness and benefit-cost analysis of the Estonian speed camera program on observed roads. Finally, thesis limitations, implications and future research directions have been provided.

2. Literature review

The scientific literature has a wide variety of studies about the effectiveness of different speed camera networks, and there are overlapping patterns and common variables on how the effectiveness of any speed camera program could be measured after the deployment. The current studies are sketchy about the economic view, and thus this thesis literature review will map the optimal set of key performance indicators (KPI) from the previous studies and finds out how to calculate the benefit-cost ratio for any future speed camera program. This thesis will use the identified KPI's to calculate the cost-effectiveness and benefit-cost ratio of current Estonian speed camera program.

To identify proper studies, following sources were used: internet sources including governments, universities, and research agencies homepages (1), electronic traffic safety databases (2), the road safety technical library database (3) and science articles databases Science Direct, Google Scholar, EBSCO Discoverer (4). All studies had to be in English or Estonian language and completed before 2017. Studies were reviewed to determine whether they describe an evaluation of the automated speed enforcement program that included safety-related outcomes like crashes, injuries, deaths, speed measurements, effective range estimations, detailed economic evaluations and provided detailed descriptions of study methods and detailed results.

2.1 The public safety investments analysis models

In the literature, there are several types of research and handbooks how to make an economic analysis of crime prevention. The two primary complementary ways of estimating the feasibility of crime prevention program are cost-effectiveness and benefit-cost analysis as shown in Figure 1 (McIntosh, Li 2012). This economic approach can also be adapted for analyzing the traffic safety or other accidents prevention programs.

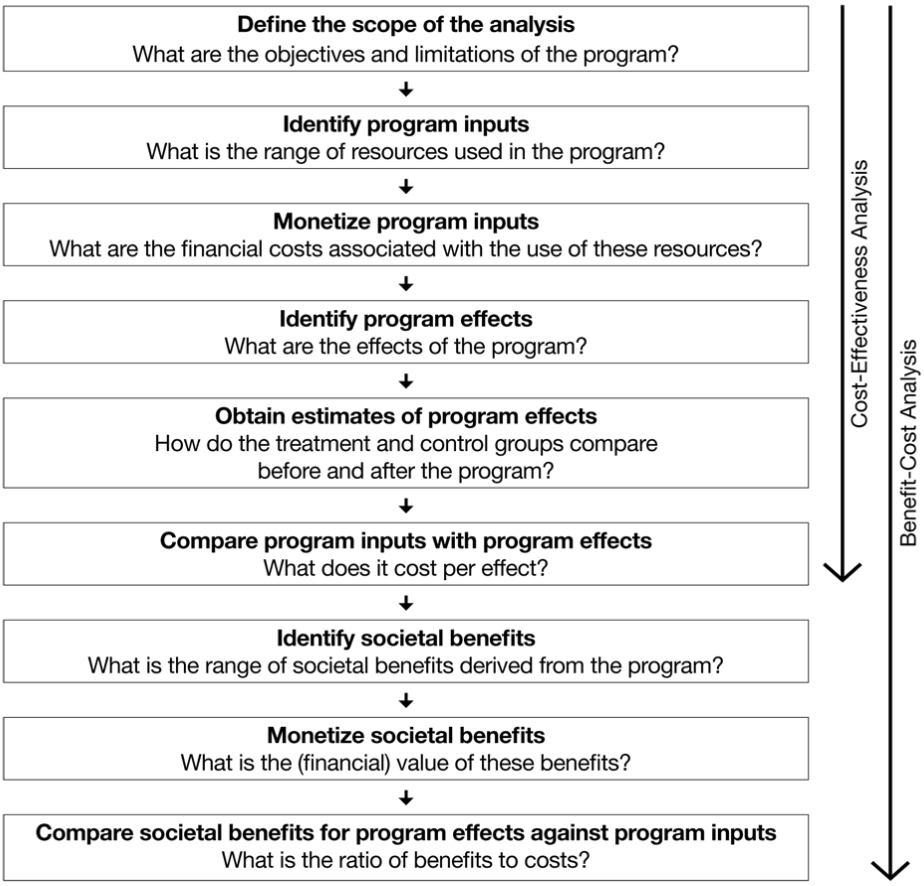

Figure 1: The primary steps of cost-effectiveness and benefit-cost analysis of crime prevention program (McIntosh, Li 2012).

The economic analysis has to include at least two variables: measurable crime prevention effects and measurable crime prevention costs (McIntosh, Li 2012). According to Levin (1995), before the measurements, it is necessary to understand the prevention problem, and after the problem has been defined, the scope of analysis is set. Then it will be necessary to analyze how to measure the prevention effectiveness, which alternatives are possible, what are the impacts of alternatives, and what inputs are needed for economic analysis (Levin 1995).

The inputs data should be quantitative than qualitative when planning measurements, as the quantitative data is a more obvious choice and it can directly connect to costs and benefits. The qualitative data needs first to interpret, and there is a higher risk of misinterpreting the context and thus giving different input to economic models (Welsh, Farrington 2000). When the effects are measured then the associated resources and related costs must be identified and this way the program inputs get monetized (McIntosh, Li 2012). To obtain the estimates of the program effects the before-and-after method (BA), with comparison groups, are widely used. When complementing BA analysis data with the related costs, the cost-effectiveness analysis is done (McIntosh, Li 2012).

The purpose of cost-effectiveness (CE) analysis in crime prevention is to give additional information to policy and decision makers about how much funds are used or needed to get an effect (Chisholm 2000; Welsh, Farrington 2000). CE gives information about the financial relationship to non-monetary net effects to audit the project later or to rank it with other preventive measures. It does not give any benefit information about the effect on society and is somewhat incomplete regarding benefits (McIntosh, Li 2012).

The cost-effectiveness (CE) is calculated by dividing the total program cost with the net effect of the program (Welsh, Farrington 2000), and is expressed in Equation 1.

$$CE = \frac{Total\ Program\ Cost}{Net\ Effect\ of\ Program} = \frac{Total\ Program\ Cost}{Effect_{Intervention} - Effect_{Control}}$$

Equation 1: The calculation of cost-effectiveness ratio (McIntosh, Li 2012).

The total program cost is the sum of all costs related to that program; like administrative cost (salaries, training), capital costs (office, equipment, transportation) and indirect costs like sponsoring and providing for volunteers. The net effect of the program stands for the program’s non-monetary effects measured in a determined timeframe against the other scenarios like if the program has not implemented (Levin, McEwan 2000; McIntosh, Li 2012).

In the example of McIntosh and Li (2012), if for some reason, the number of car accidents exceeds 100, then the causes need to be treated. Then the intervention program of car accidents reduction includes increasing the highway patrols in the region. To increase the number of patrols a new team of Traffic Police Officers must be hired. The extra cost is 100 000 euros per year (office, salaries, and equipment). If after intervention the car accidents with injuries have fallen to 50 per year, then the CE is found by dividing the total program cost of € 100 000 to 50 car accidents with injuries prevented. That is 2000 euros per car accident with injuries prevented.

The cost-effectiveness ratio is the monetary relationship per number of achieved net effects and is useful for auditing or ranking different initiatives with the same dimension (Welsh, Farrington 2000). CE does not give beneficiary information to society. To overcome this limitation, it can be developed further to give the monetary benefits for the society, and this is the benefit-cost analysis (Welsh, Farrington 2000; McIntosh, Li 2012). For estimating the benefits for the society, the effects of the program must be measured and monetized. In the benefit-cost analysis, the benefits are the savings for the society (Welsh, Farrington 2000).

The benefits and costs can be tangible and intangible. The tangible costs are, for example, insurance related costs and costs to replace damaged property or running prevention program. The intangible costs are calculated hypothetical lost income or future profits. In public sector view, the “profit” is instead of avoiding potential losses (Chisholm 2000; Levin, McEwan 2000; Welsh, Farrington 2000; McIntosh, Li 2012).

The purpose of benefit-cost analysis in crime prevention is to give additional information to policy and decision makers about the benefits of society per euro invested (Welsh, Farrington 2000).

To make an economic evaluation we have to introduce new variables like the Potential Societal Savings (PSS) per undesired key performance indicators (KPI) like the number of crimes, accidents or fatalities. The PSS includes all tangible and intangible costs to victims, insurances, the criminal justice system and other stakeholders that will be avoided per number of KPI. The KPI’s are the net effects in numbers that the prevention program helps to achieve (McIntosh, Li 2012). The calculation is expressed in Equation 2.

$$BCR = \frac{Potential\ Soceietal\ Savings\ (per\ KPI) \times Net\ Effect\ of\ Program\ (KPI\ averted)}{Total\ Program\ Cost}$$

Equation 2: The calculation of the benefit-cost ratio (McIntosh, Li 2012), adopted by the author.

Let's assume that PSS is 5000 euros per car accident with injured person (cost of KPI in euros), and the accident reduction (KPI averted) is 50. Then the benefit-cost ratio (BCR) is found by multiplying the PSS per accident to the net effects of the program (the KPI averted) and then dividing it with the total costs of the program (McIntosh, Li 2012). BCR is found by multiplying 5000 euros per car accident to 50 car accidents averted and then dividing it with the program cost of 100 000 euros, which is 2.5. When we subtract the investment, then the society would save extra 1.5 euros per every invested euro. BCR is useful for ranking different prevention initiatives by monetary value (Welsh, Farrington 2000).

2.2 Speed enforcement theory

The most common argued reason for speed enforcement has been the traffic safety and most empirical studies in traffic safety will support the postulated theories about the relationship between the car speed, accident risk, and collision severity (Chen et al. 2002). It has been widely theorized that the higher the speed of a car the higher the risk of accident and thus the more severe are the collision consequences (Fildes et al. 1991). Some researchers have generalized that for every 1-km/h increase in mean traffic speed above the speed limit will increase the accident risk around 3% (Finch et al. 1994). The simplified explanations based on raw physics as the stopping distance of speeding car will increase exponentially, and the accumulated energy will dissipate in the accident to the power of two of the impact speed (Fildes et al. 1991). On the other hand, more elaborate studies argue that the higher speeds do not always mean higher accident risk and are rather dependent on the design and condition of the road and collision risk will be increased by the speed variance between individual vehicles on the same road (Chen et al. 2002).

2.3 The speed camera system effectiveness for reducing accidents

There are two major ways to enforce speed limits - the manned and automatic speed control. The classic way relies heavily on the manned police patrols on the street. It has been argued that speed enforcement deterrence effect achieved through uncertainty as the speed checks will take place in random locations and times on the road corridor (Chen et al. 2002).

Sometimes prevention of further violations will be achieved by personal contact while the officer is issuing a ticket on the spot. It is quick and clear punishment for the errant drivers as officers usually reinforce the infringement with warnings and educational messages (Tay 2007).

Some researchers argue that manned enforcement cannot permanently reduce speeding behavior and accidents as the lack of resources and driver's motivation are not enough to cause permanent deterrence effect everywhere. Therefore, the automated speed enforcement should be a reasonable complement to manned patrols (Elvik 1997; Newstead et al. 2001).

Automatic speed enforcement based on general deterrence theory where potential violators will refrain from speeding as they desire to avoid punishment or other legal consequences (Ross, 1982). As the speed camera system works 24/7, the likelihood of being detected and punished is almost inevitable. It has been hypothesized that automatic speed enforcement programs would regress the traffic speeds towards the mean speed and will also reduce the variance of traffic speeds at the speed camera deployment sites (Chen et al. 2002).

The automatic speed limit enforcement solutions have been deployed for 30 years. There are many different speed camera systems in place in many countries, and several research groups have studied the effectiveness of single systems. Thus, there are a variety of studies about the effectiveness of the local system and also several literature reviews about the previous studies. For the literature review of this thesis, the primary interests are the effectiveness and economic feasibility analyses of the speed camera networks.

In total, 16 studies met the inclusion criteria and were analyzed for the literature review. The literature overview in Table 1, the first column is authors and year to give an overview of the variety of studies done in the automated speed enforcement area. The description of camera network is added to give an overview of the camera types the observed studies used. The static speed cameras are stationary systems, the mobile speed cameras are movable and change the measuring sites. In the observation method section, there are overviews of methods used for analyzing the results, and in the key performance indicator section, you can find an overview of the main findings of the selected studies in a comparable way.

Table 1: The literature review with main findings

Study, authors, year	**Description of the static speed camera network**	**Used observation methods**	**Key performance indicators (KPI), reductions or other effects**
Elvik (1997)	Cameras: 64 (static); Site: Norway: Evaluation period: Three years before and after	Before and after study;	Crashes: -12% Injuries: -20%
Mountain, Hirst, Maher (2004)	Cameras: 62 (static) Site: Across UK Evaluation period: Three years before and after	Empirical Bayes;	Speed: -6%; Speeding: -35%; Crashes: -25%; Injuries: -11%; Deaths: -11%; Crash migration: +5%; Effect range: 500m; Safety spillover: 1km effect
Mountain, Hirst, Maher (2005)	Cameras: 79 (static) Site: 79 sites, UK Evaluation period: Three years before and after	Empirical Bayes;	Speed: -4% Speeding: -33% Crashes: -6% Injuries: -20% Deaths: -24%
Pérez, Marí-Dell'Olmo, Tobias, Borrell (2007)	Cameras: 8 (static) Site: Barcelona, Spain Evaluation period: Two years before and after	Time-series study with a comparison group;	Crashes: -27% Injuries: -26%
Hess, Polak (2007)	Cameras: 43 (static); Site: Cambridgeshire, UK; Evaluation period: 11 years of time series data collection	ARIMA/SARIMA (remove trend and seasonal effects) time series analysis; Before and after comparison;	Crashes: -32% Injuries: -31% Deaths: -28% BCA: 1:5
Shin, Washington, Schalkwyk (2009)	Cameras: 6 (static) Site: Scottsdale, Arizona, US Evaluation period: Two years	Before and after analysis using a comparison group and traffic flow correction; Empirical Bayes analysis with time-variant safety;	Speed (average): - 14km/h Crashes: - 44% to -54% Injuries: -28% to -48% Deaths: - 46% to -56% BCA: $17 million per year Safety spillover: None
Li, Graham. (2013)	Cameras: 771 (static) Site: Across UK Evaluation period: Three years before and after	Propensity score matching; Empirical Bayes; Control sections for matching observations;	Crashes: -23% to -31% Deaths: -3% to -11% Crash migration: None Effect range: 200 - 500m

Table 1: continued.

Carnis, Blais (2013)	Cameras: 2756 (static); Site: France Evaluation period: 2 years before and seven years after	Interrupted time-series analyses;	Injuries: -26% Deaths: -21%
Äär (2014)	Cameras: 56 (static) Site: Main roads, Estonia Evaluation period: Three years before and after	The before and after study with comparison group; Empirical Bayes;	Crashes: reduction in Tallinn – Narva road; Injuries: inconclusive, the national trend is higher; Deaths: inconclusive, the national trend is higher; Effect range: 200m
Keall, Povey, Frith (2001)	Cameras: n/a (mobile) Site: 4 sites in New Zeland Evaluation period: One year before and after	Interrupted time-series design with comparison group;	Speed (mean): - 0,7 km/h Crashes: -11% Injuries: -19% Deaths: -8% Safety spillover: Yes
Chen, Meckle, Wilson (2002)	Cameras: 12 (mobile) Site: 22km highway in British Columbia, Canada; Evaluation period: Two years before and after	Simple before and after; Empirical Bayes;	Speed: -3% Crashes: -16% Crash migration: None Safety spillover: Yes
Christie, Lyons, Dunstan, Jones (2003)	Cameras: 101 (mobile) Site: South Wales, UK Evaluation period: Three years before and one year after	Controlled before and after study with a circular zone around the camera and a route based method;	Injuries: -50% Effect range: 300 - 500m
Newstead, Cameron (2003)	Cameras: mobile, 2500 random measuring sites Site: Queensland, Australia Evaluation period: Five years before and after	Quasi-experimental A study design with Poisson log-linear statistical model;	Injuries: -21% Deaths: -32% BCA: 1:47 Crash migration: n/a Effect range: 500 – 1500m Safety spillover: Yes
Gains, Heydecker, Shrewsbury, Robertson (2004)	Cameras: 2300 (mixed) Site: 23 sites UK Evaluation period: Three years before and after	Simple before and after; Empirical Bayes;	Speed: -7% Speeding: -91% Crashes: -22% Injuries: -42% BCA: 4:1
Goldenbeld, van Schagen (2005)	Cameras: 28 (mixed) Site: Rural roads Friesland, Netherlands Evaluation period: 5 years before and eight years after	Before and after study with an experimental (targeted speed enforcement) and a comparison (no targeted speed enforcement) condition;	Speed (mean): -4 km/h Speeding: -12% Crashes: -21% Injuries: -22%
Jones Sauerzapf, Haynes (2008)	Cameras: 29 (mobile) Site: Norfolk, England Evaluation period: Two years before and after	Before and after analysis;	Crashes: -19% Deaths: -44% Crash migration: No

Source: compiled by the author.

For easier comparison, the following indicators were defined: (1) The speed to indicate the effects to mean speeds. (2) The speeding to indicate the effect of reducing speeding. (3) The crashes are for indicating the effects of accidents without injured people. (4) The injuries are for indicating crashes that involved at least one person injured. (5) The deaths for indicating crashes that involved at least one death. (6) The BCA is to indicate if the benefit-cost analysis has done and what was the result. (7) The crash migration is for indicating if the study observed accident migration to other roads or no camera sections in the road corridor. (8) The effects range is for indicating the speed camera systems effective range, (9) The safety spillover is to indicate if the study observed overall safety increase outside of the speed cameras effective range due to the speed cameras.

To summarize the main findings of the literature review in Table 1: the relative reduction in average speed ranged from 3% to 7% and the reduction in the proportion of vehicles speeding ranged from 35% to 91%. Collision reductions varied 10% to 50%, injuries reduced 20% to 50% and deaths reduced 21% to 35% in the vicinity of camera sites. There is minor evidence of accident migration (Mountain et al. 2004) on the highway corridor or parallel roads. Several studies observed the speed reduction over broader geographical areas and thus found the negative impact to traffic flows (Goldenbeld, van Schagen 2005; Mountain et al. 2004).

The safety spillover effect along the road was observed with only mobile speed cameras; static cameras had an effective safety range of 200 – 1000 m. After 1500 m, the effects were similar to no treatment zones (Shin et al. 2009; Mountain et al. 2004; Li et al. 2009; Christie et al. 2002). The difference between the safety spillover of static and mobile speed cameras effect comes from the unpredictable deployment time and location of the mobile cameras thus it has increased deterrence effects to keep posted speed limits along the road corridors (Chen et. all 2002; Newstead and Cameron 2003).

Methodically the most common way of traffic safety studies is before-and-after observations with and without controlled comparison roads. The main pitfall of using naive before-and-after studies is to ignore the national traffic safety trend and the accidents regression-to-mean (RTM) on sites where there have been historically high accident rates (Elvik 1997; Hauer et al. 2002; Mountain et al. 2004).

The trend means that the traffic safety also increases by other means like safer cars, better roads, public campaigns, police interventions and changes in traffic flows. To correctly evaluate the effects of speed camera networks the other safety effects should be measured and excluded. Otherwise, the camera networks effects are most likely incorrectly estimated (Elvik, 1997; Mountain et al. 2004; Hirst et al. 2004).

The RTM effect is a random fluctuation of accidents, and it should be calculated when there is high probability it distorts the safety-related estimations considerably (Elvik, 1997). To disaggregate the RTM effect, the Empirical Bayes method (EB) used in many studies. It has argued, that EB increases the precision of estimates when there is limited safety-related data available like a low number of accidents or a short observation period (2-3 years), and it corrects the RTM bias more accurately (Elvik, 1997; Mountain et al. 2004; Hirst et al. 2004). However, in the five year evaluation period, the RTM effect is around 5-10% of accidents (Goldenbeld, van Schagen 2005). The EB is the standard method for estimating the RTM effect in traffic accidents research (Hauer et al. 2002; Mountain et al. 2004; Lord et al. 2010).

2.4 The primary key performance indicators of automatic speed enforcement.

From the literature review in Table 1, all the studies contain one or all of the following key performance indicators (KPI): (a) Minor crash reduction which represents the car accidents where there are no human casualties. In Estonia, these are primarily traffic insurance cases, and the police will be involved only if the parties to the traffic accident do not reach an agreement on the perpetrator; (b) Injuries reduction, which represents all cases where at least one person needs medical attention after the car accident; (c) Fatalities reduction, which represents all the cases where an injured person dies within 30 days after the accident. The police must be involved in cases b and c (Liiklusseadus, 2018).

These key indicators are affected by several other variables. From the literature review, the following variables were identified: vehicle speeds and speeding. The higher the speeds, the more severe are the consequences of the accident and the more likely the accident is to occur (Finch et al. 1994). Speeding means that the variance between vehicle speeds increased and thus more overtaking maneuvers also increase the risk of accidents (Chen et al. 2002). Speeding also increases the traffic fluctuations (kangaroo jumps) that in turn reduce the traffic flow and affects the mean speed, traffic density and crash migration in the highway corridor (Chen et al. 2002; Mountain and Hirst 2004).

3. Methods

In order to calculate the benefit-cost ratio for speed camera network, the following steps will be made:

1. Define the scope of economic analysis through literature review (chapters 2.1 to 2.3)
2. Define the key performance indicators (chapter 2.4)
3. Acquire and analyze the available data (chapters 4.1 to 4.6).
4. Identify the effectiveness of the speed camera program (chapters 3.2, 5.1 and 5.2).
5. Identify the cost of the speed camera program (chapters 3.3 to 3.4 and 5.3).
6. Identify the tangible and intangible savings for the society (chapters 3.4 and 5.4).
7. Calculate the effectiveness of speed camera groups (chapters 3.3 and 5.5).
8. Calculate the benefit-cost ratio of the speed camera program (chapters 3.4 and 5.6).

3.1 The effectiveness of speed camera program

For determining the effects of the speed camera program, the before-and-after method with comparison groups is used. By looking nationally, we observed road based accident data and comparing it with the speed camera effect zones of one-kilometer range from speed camera measuring cabin installment. The one kilometer range for up and down the road has shown proven effectiveness, regarding the boundaries of static speed cameras from the literature review (Chen et al. 2002; Newstead and Cameron 2003; Li et al. 2013). For eliminating the inaccuracy risk of RTM effect, the extended dataset from 2003 to 2017 is used and recommended by Goldenbeld and van Schagen (2005).

An extra two km buffer zone is added between the camera enforcement zone and comparison group by the author to remove any spillover effects to the comparison group, as some researchers have measured the camera effects up to 1.5 km from speed cameras (Newstead and Cameron 2003). The before-and-after method is used to compare the number of accidents, fatalities, and injuries on the observed periods and in combined form is referred as KPI.

3.2 The before-and-after method with comparison groups

The observed speed camera zones effectiveness is measured by using the before-and-after method with comparison group method described first by Hauer (1997). This method removes the traffic safety trend effect that usually causes the overestimation of the speed camera intervention (Hisrt et al. 2004). The control groups are sections of the observed road without speed cameras and are similar in physical characteristics, accident rates. For example, the four-lane highway sections are excluded as these are not comparable with the ordinary road with two lanes. The trend is found by taking the average of control groups and comparing it with the accident data of the before and after the speed camera deployment. For a more accurate estimation, the control group is compared with the speed camera zones to calculate the comparability odds ratio. If the odd is near one, then the groups are comparable (AASHTO 2010). For calculating the effectiveness of speed camera networks the variables and equations are described by Hauer (1997) and Hisrt et al. (2004). The KPI is representing minor crashes, accidents, fatalities or injured persons in traffic accidents. The variables of the before-and-after method used are:

- tB = time in years before speed camera program intervention;
- tA = time in years after speed camera program intervention;
- $KPI_{BfNoCam}$ = KPI in numbers before tB on the control group road with no cameras;
- $KPI_{AfNoCam}$ = KPI in numbers after tA on the control group with no cameras;
- KPI_{BfCam} = KPI in numbers before tB on the 1000m range of observed the road with cameras;
- KPI_{AfCam} = KPI in numbers after tA on the 1000m range of observed the road with cameras.

To find the comparability of the control group and enforcement zone the odds ratio (OR) of accidents (Acc) is found by using Equation 3. If the OR is between 0.9 and 1.1, both groups are similar with the confidence of 95%. If OR >0.9 then the control group performs under the treatment group and if OR < 1.1 the treatment group performs over the comparison group (AASHTO 2010). The OR is found by dividing the relationship between the multiplication of the camera site accidents before the camera intervention (KPI_{BfCam}) with the accidents of the control group of after the camera intevention (KPI_{BfCam}) with the multiplication of the camera site accidents after the camera intervention (KPI_{AfCam}) with the accidents of the control group of before the camera intevention ($KPI_{BfNoCam}$) with the sum of one, inverse relationship of accidents of camera site after camera intervention($1/KPI_{AfCam}$) and inverse relationship of accidents of control group ($1/KPI_{BfNoCam}$) before the camera intervention (Hisrt et al. 2004). The equation is presented by Equation 3, and the results are in Table 7.

$$OR = \frac{(KPI_{Bf_{Cam}} \times KPI_{Af_{NoCam}})/(KPI_{AfCam} \times KPI_{BfNoCam})}{1 + \left(\frac{1}{KPI_{AfCam}}\right) + (\frac{1}{KPI_{BfNoCam}})}$$

Equation 3: The comparability odds ratio (Hisrt et al. 2004), adopted by the author

In order to calculate the reduction of accidents in percentage, the average number of accidents of after period is subtracted from the average number of accidents of the before period, and the difference is divided by the average of accidents of the before period (Hisrt et al. 2004). This relationship is expressed by the Equation 4. The results are presented in Table 7.

$$AR\ (\%) = \frac{\frac{KPI_{AfCam}}{tA} - \frac{KPI_{BfCam}}{tB}}{\frac{KPI_{BfCam}}{tB}} \times 100\%$$

Equation 4: The KPI reduction (AR) % (Hisrt et al. 2004), adopted by the author

The number of the expected KPI (KPI_E) after the observed period, if cameras have not deployed, is found by multiplying the KPI before (KPI_{BfCam}) the intervention of the camera system with the relationship between the KPI of after period ($KPI_{BfNoCam}$) and KPI of the before period ($KPI_{BfNoCam}$) of the control group (Hisrt et al. 2004). The results are presented in Table 7.

$$KPI_E = KPI_{BfCam} \times \frac{KPI_{AfNoCam}}{KPI_{BfNoCam}}$$

Equation 5: The expected KPI in numbers (Hisrt et al. 2004), adopted by the author

The effect of speed cameras (ESC) in KPI is found by the subtracting the average KPI of after the camera intervention from the average of expected KPI_E over the same period (Hisrt et al. 2004). The results are presented in Table 7.

$$ESC = \frac{KPI_{AfCam}}{tA} - \frac{KPI_E}{tA}$$

Equation 6: The effectiveness of speed cameras by KPI (Hisrt et al. 2004), adopted by the author.

3.3 The cost-effectiveness analysis of speed camera program

The goal of cost-effectiveness in this thesis is to show how much impacts are costing in the context of preventing traffic accidents. The calculation equation of the cost-effectiveness analysis (CE) of traffic safety program is found by dividing the speed camera program cost with the total prevented KPI (McIntosh, Li 2012) as shown in Equation 6. The results are presented in chapter 5.5.

$$CE = \frac{Speed\ camera\ program\ cost}{KPI\ prevented\ by\ program}$$

Equation 7: Calculating the cost-effectiveness (McIntosh, Li 2012), adopted by the author.

The program cost includes personnel, processing, and capital costs (McIntosh, Li 2012), and can be described as the sum of disaggregated costs and is illustrated by Equation 8. The results are presented in chapters 4.3 and 4.4.

$$Speed\ camera\ program\ cost = I + S + P$$

Equation 8: Calculating the cost of speed camera program (McIntosh, Li 2012), adopted by the author.

Where the speed cameras program cost can be found by adding the cost of infrastructure (I), the cost of written warning software (S) and the cost of Police processors work (P).

The KPI prevention will involve all savings the intervention causes. The speed camera program's effect is found when the trend, RTM, and KPI values are subtracted from the period prior to the intervention. That will involve all losses and cost caused by traffic accidents (McIntosh, Li 2012; Hirst et al. 2004). KPI’s prevented by the program is illustrated by Equation 8. The results are presented in chapter 5.6.

$$KPI\ prevented\ by\ program = KPI(before) - Trend - RTM - KPI(after)$$

Equation 9: The calculation of the KPI (McIntosh, Li 2012; Hirst et al. 2004), adopted by the author.

3.4 The benefit-cost analysis of the speed camera program

When analyzing the benefit-cost model of crime prevention, reconciling community spending on money is the direct benefit of preventing crime or accidents from extracting economic benefits from an investment. Ordinary profits are replaced by societal savings that could be lost in the absence of a program (Levin, McEwan 2000; Cohen, Piquero 2009; McIntosh, Li 2012). However, speed camera programs usually earn some revenue by sending fines for speeders, and this should be included as a benefit as this puts the burden on the speeders and thus reduces the program cost to the whole society.

Benefit-cost analysis (BCA) shows, in the view of prevention programs, how many euros a society saves in every euro invested (Levin, McEwan 2000). This result can be used to evaluate the impact of alternative programs (Welsh, Farrington 2000). The equation for calculating the benefit-cost ratio for speed camera program is in Equation 9. The results are presented in chapter 5.6.

$$BCR = \frac{(Averted\ Societal\ Costs\ \times\ KPI\ prevented\ by\ program) + Revenues}{Program\ Cost}$$

Equation 9: The calculation of benefit-cost ratio (McIntosh, Li 2012), adopted by the author.

To calculate the cumulative monetary effects of traffic safety program, the effects of crashes ($KPI_{crashes}$), accidents ($KPI_{accidents}$), injuries ($KPI_{injuries}$), and fatalities ($KPI_{fatalities}$), will be monetized by the values crash (C_{crash}), accident ($C_{accident}$), injuries ($C_{injurie}$), fatalities ($C_{fatalitie}$) and summarized as illustrated in Equation 10. The results are presented in chapter 5.6.

$$Averted\ Societal\ Costs\ \times KPI\ prevented\ by\ program = (KPI_{crashes} \times C_{crash}) + (KPI_{accidents} \times C_{accident}) + \left(KPI_{injuries} \times C_{injurie}\right) + \left(KPI_{fatalities} \times C_{fatalitie}\right)$$

Equation 10: The monetization of benefits (McIntosh, Li 2012), adopted by the author.

Adverted Social Cost includes all negative effects and costs related to KPI (McIntosh, Li 2012), for details, see Table 7. The annual revenues of the speed camera program of Table 6 are summed and added to the benefits. All monetary calculations are rounded to full euros

4. Data

In the data section, the Estonian speed camera and traffic safety program is introduced with the accident data and dynamics form 2003 to 2017. The program inputs and costs are divided into the prevention costs, the development and maintenance costs of speed camera infrastructure, the software development costs for written warning procedure, the control costs, the costs of consequences, and the revenue from written warning procedure.

4.1 The Estonian speed camera program

According to the Estonian Road Administration (ERA), on December 1, 2017, 66 measuring cabins are on the national roads of Estonia as shown in Table 2, of which four can measure the speed in both directions. Also, the ERA has two-speed cameras in the city of Tallinn. ERA uses 47-speed cameras, which are reposted from time to time between the measuring cabins. The study uses road accident data that is within one-kilometer range of areas covered by speed cameras. The locations of speed camera measuring cabins are shown in Figure 2.

The speed camera system and written warning procedure only affect the roads covered by the speed cameras (Table 2). International studies have shown that the speed cameras have the most effective spatial coverage on average 500m before and after a speed camera (Li, 2013).

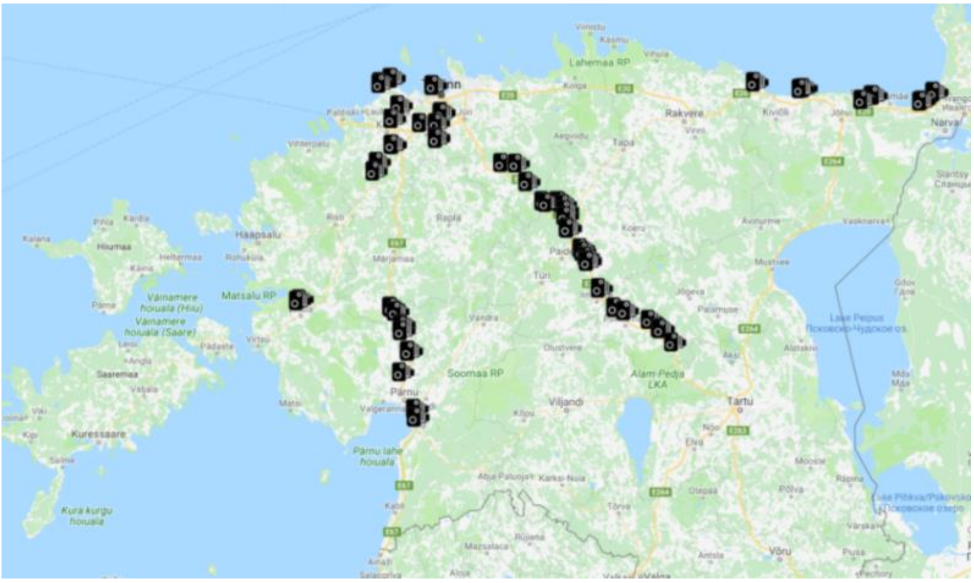

Figure 2: The locations of Estonian Speed Cameras (ERA, 2018).[2]

[2] Map of speed camera locations (ERA 2018): http://tanel.jairus.ee/kiiruskaamerad.html

Table 2: The location, number and year of implementation of Estonian speed cameras.

Road	No of camera measurement cabins	Operational year
Tallinn-Tartu-Võru-Luhamaa	24	2011
Tallinn-Pärnu-Ikla	11	2011
Tallinn-Narva	11	2013
Ääsmäe-Haapsalu-Rohuküla	4	2014
Saku-Laagri	1	2014
Tallinn-Rannamõisa-Kloogaranna	4	2014
Tallinn-Rapla-Türi	5	2014
Tallinn-Paldiski	4	2016
Risti-Virtsu-Kuivastu (excluded)	2	2017
Tallinn at Kristiine crossing (excluded)	2	2017
Total	**68**	

Source: ERA (2018)[3], compiled by the author.

The Risti-Virtsu-Kuivastu and Kristiine crossing speed cameras are excluded from this thesis as these have been installed in December of 2017 and don't have annual data for doing BA analysis.

4.2 The Estonian Road Safety Program

The Estonian Traffic Safety Program 2016-2025 aims to reduce traffic accidents to less than 40 people per year and the number of injured, three consecutive years on average, down to 330 people per year. The traffic accidents data for this thesis acquired from the Police and Border Guard Board (PBGB), Estonian Road Administration (ERA) and Estonian Traffic Insurance Fund (ETIF). Table 3 presents the number of minor crashes (Crash), serious traffic accidents (Acc) with fatalities (Fat) or at least one person injured (Inj) between 2003 and 2017. To illustrate the implementation and dynamics of the Estonian road safety program 2003-2015 the Figure 3 and 4 presents the annual change in observed categories. A minor crash is an accident where there is an only financial loss. The serious accident must have at least one person injured. Fatalities are all cases where a person dies as a result of a traffic accident on the spot or within 30 days in a hospital. All persons who are in stationary care for more than 24 hours are considered injured (Traffic Year 2016).

[3] Locations of speed cameras (ERA 2018): https://www.mnt.ee/eng/roads/cameras-speed-limit-enforcement/camera-locations

Table 3: The number of traffic accidents and consequences from 2003 – 2017.

KPI	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Crash	3644	3978	3886	4780	4687	4205	3341	3248	2989	2928	3022	3227	3351	3107	3234
Acc	1675	2201	2340	2585	2442	1851	1193	1177	1475	1377	1373	1425	1374	1462	1407
Fat	131	167	171	206	197	125	85	76	92	84	79	77	67	71	48
Inj	2184	2811	3029	3515	3254	2357	1482	1466	1880	1704	1704	1732	1719	1842	1727
Total	**5319**	**6179**	**6226**	**7365**	**7129**	**6056**	**4534**	**4425**	**4464**	**4305**	**4395**	**4652**	**4725**	**4569**	**4641**

Source: Police and Border Guard Board (2018), compiled by the author.

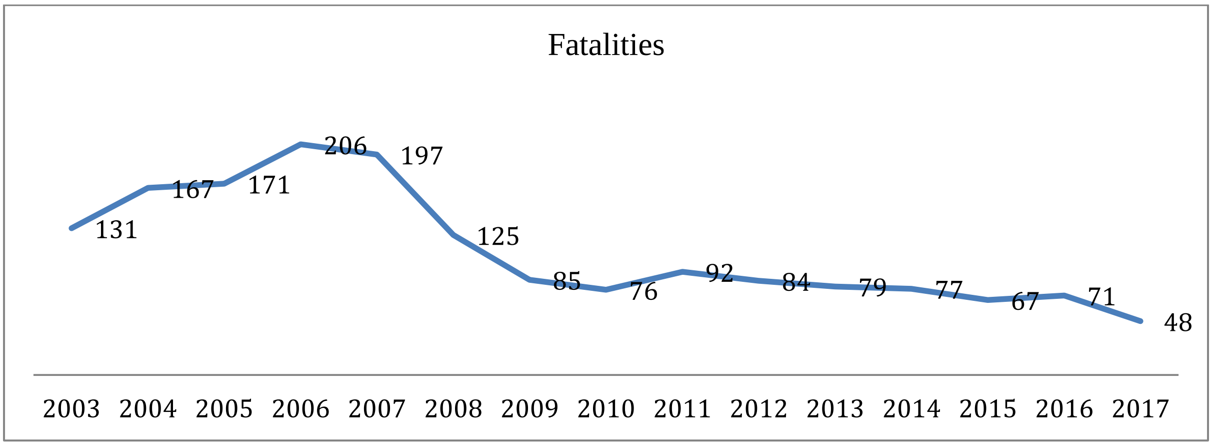

Figure 3: Dynamics of traffic accident fatalities from 2003 to 2017 from Police and Border Guard Board, compiled by the author.

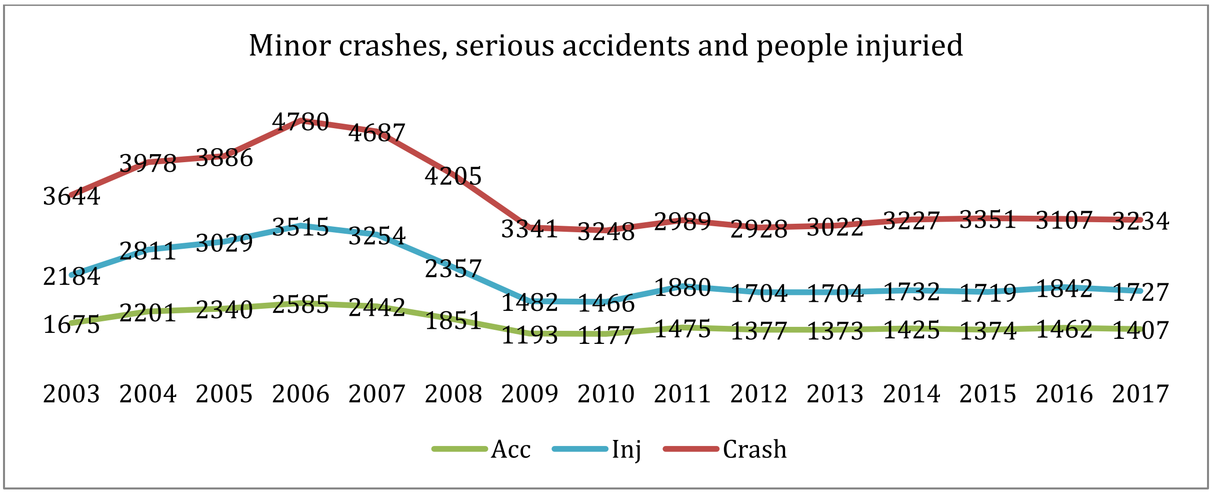

Figure 4: Dynamics of crashes, serious traffic accidents and injuries since 2003 to 2017 from Police and Border Guard Board, compiled by the author.

A classic measure of speed control is the speed measurement of the speed by police patrols. The disadvantage of this measure is its short-term effectiveness. Estonia has not enough resources to measure the speed of vehicles on every dangerous road section (Prooses 2007). From 2009, an automatic speed control system and a written warning procedure have been developed to address this shortcoming. This system installed on the most dangerous sections of the road. It is traffic calming preventive measure to reduce road accidents due to excessive speed (Traffic Safety Program 2003-2015).

Overall traffic offense costs fall into three categories: prevention costs, control costs, and consequence costs. The corresponding costs, in turn, are divided into tangible and intangible costs (McIntosh, Li 2012). Historical research data cover the control costs and consequence costs. This work focuses on the prevention costs of traffic accidents. There are insufficient studies on prevention costs in Estonia (Kallaste et al. 2015: p.127).

4.3 The prevention costs

All investments that reduce the number of harmful events are considered as prevention costs. These would be the development and maintenance costs of speed camera infrastructure and related software (see Equation 8). The relevant data acquired from Estonian Electronic Procurement Registry (e-PPR) and Estonian Road Administration.

4.3.1 The development and maintenance costs of speed camera infrastructure

Altogether, on the dangerous road sections, by 2017, 68 measurement cabins and 47-speed cameras are operated, with a total cost of 4 083 060 euros according to the e-PPR. The corresponding costs are the purchase of equipment, maintenance, relocation of cameras and infrastructure connections like electricity and communications. The infrastructure costs are characterized by Appendix 1.

4.3.2 The Software development costs for written warning procedure

According to the e-PPR, the cost of software development and maintenance for written warning procedure is 645 495 euros. It includes the creation of an information system, interfacing with other information systems, purchasing hardware and continuing development work. The cost of the written alert information system is characterized by Appendix 2.

4.4 The control costs

In this study, the control costs are all costs related to the work of misdemeanors. This includes wages, office and equipment costs. According to the wage and labor data published by the Ministry of Finance, the average gross salary for the respective position presented in characterized in Appendix 3 and is 1255 euros per month. The total monthly cost to the public sector, with the national labor tax (33%), is therefore 1679 euros per month. According to the police, a particular unit is working on automatic speed enforcement infringements. As a result, the annual salary of the job is 1679 euros multiplied with 12 months and 12 posts (in 2017), and that is 80 592 euros. The estimated total cost of one a workplace is 2968 euros per month according to the public document registry of ERA (2018)[4]. It includes all the costs related to the office workplace like security, electricity, internet, heating and payments by PBGB to the office building owners and to the other important service providers. Working equipment is 500 euros for a four year period per one official.

4.5 The costs of consequences

In this thesis, the costs of crashes, accidents, fatalities, and injuries to society are acquired from other authors (Koppel et al. 2005). The costs of consequences are divided into two parts - tangible and intangible costs.

The tangible costs are the cost of treatment for the hospitals and to the victims, the cost of temporary or permanent incapacity to work for the Social Insurance Board. In the event of a fatal road accident, the costs are the survivor's benefit (dependents) and funeral expenses (Koppel et al. 2005; McIntosh, Li 2012).

The intangible costs are the loss of future income, the cost of the psychological suffering for the deaths of loved ones, and for the employer the loss of production caused by the death of a worker (Koppel et al. 2005; McIntosh, Li 2012).

All these variables are taken into account by Koppel et al. (2005) and are included in the cost model in Table 4 and will not be disaggregated in this thesis (for details look, Koppel 2005).

Table 4 illustrates the costs of fatalities, injuries, and accidents. As the values were calculated in 2005 by Koppel, the costs are upgraded to meet the 2017 values. For this reason the previous costs of fatalities, injuries and accidents are updated by using the annual growth of GDP. Unfortunately, there is no data to add to the minor crashes column.

[4] Estonian Road Administration, 2016, Public documents registry: 1-21/16-00026/117; https://adr.mkm.ee/?id=AF5E49C74039089FC225805E002B536F

Table 4: The cost of fatalities, injuries, and accidents in euros.

Year	GDP	GDP Growth	Fatalities	Injured	Accident
2003	6 353,50	12,73%	456 874	11 941	7 165
2004	7 124,60	12,14%	506 872	9 635	6 607
2005	8 313,00	16,68%	568 389	10 804	7 409
2006	10 039,80	20,77%	663 198	12 607	8 644
2007	12 118,00	20,70%	800 959	15 225	10 440
2008	12 353,10	1,94%	966 754	18 377	12 601
2009	10 600,00	-14,19%	985 510	18 733	12 846
2010	11 052,80	4,27%	845 651	16 075	11 023
2011	12 556,20	13,60%	881 774	16 762	11 493
2012	13 559,30	7,99%	1 001 713	19 041	13 057
2013	14 364,40	5,94%	1 081 739	20 563	14 100
2014	15 036,60	4,68%	1 145 969	21 784	14 937
2015	15 478,10	2,94%	1 199 596	22 803	15 636
2016	16 034,70	3,60%	1 234 818	23 473	16 095
2017	17 463,40	8,91%	1 279 222	24 317	16 674

Source: Koppel (2005) and Statistics Estonia (2018), updated by the author

Table 5 illustrates the accident and insurance payment data of Estonian Traffic Insurance Fund (ETIF). It contains all traffic insurance cases, annual average cost of all car related insurance cases and the annual average cost of all personal insurance cases related to traffic accidents. The insurance data is included to assess the direct monetary impact of speed cameras.

Table 5: The number and cost of traffic insurance cases in euros.

Year	Annual insurance cases in numbers	The average cost of car insurance case in euros	The average cost of personal damage insurance case in euros	The average insurance compensation for fatality in euros
2007	33126	1 597	2 868	12 012
2008	30116	1 622	3 049	28 618
2009	26750	1 453	2 997	21 813
2010	31752	1 344	4 923	12 257
2011	29793	1 324	6 298	48 717
2012	30706	1 351	2 571	55 343
2013	31231	1 351	4 003	59 765
2014	31061	1 485	4 585	63 313
2015	32506	1 468	4 236	66 276
2016	35392	1 542	3 602	68 222
2017	35662	1 616	3 786	70 676

Source: ETIF (2017)[5], compiled by the author.

[5] https://www.lkf.ee/et/statistika

For calculating the safety effects of speed camera program the accident data from Police and Border Guard Board is used. Detailed accident data and calculations of observed roads are available in appendix 6.

4.6 Revenue from written warning procedure

A written warning procedure gives offenders virtually automatic warning penalties. This process is not entirely automatic for legal reasons as the fine needs controlling and the decision needs a digital signature for a misdemeanor or, in the event of problems or significant infringement, the process interference. The fiscal benefit per year illustrated in Table 6. The topic, included in this thesis, is to look at the proportion of the respective revenue component to the total cost of prevention.

Table 6: The revenue in euros and the number of cases in written warning procedure.

Year	Revenue in euros	Number of written warnings
2013	909 410	43 100
2014	1 885 653	89 793
2015	2 188 824	103 353
2016	2 253 608	106 412
2017	2 314 332	109 684
Total	**9 551 827**	

Source: Police and Border Guard Board, compiled by the author.

5. Results and discussion

This chapter identifies the cost-effectiveness and benefit-cost ratio of the camera program and compares the results with the other studies.

5.1 The scope of the analysis

The scope of analysis in this thesis involves key performance indicators of road safety. The minor crashes and traffic accidents with human casualties (injuries, fatalities) on the main roads with speed camera installment. The accident data is compared with before and after the speed camera installment on the observed roads. The calculations take into account the accident trend on comparison roads, RTM effect, and separate it from the accident statistics of the observed roads.

5.2 Inputs

To calculate the effects of speed cameras on the observed road the before-and-after method with comparison group used. Whether, the comparison group, is suitable, the odds ratio calculated for all roads and their control groups. As noted in the literature review static speed cameras have the highest effective range around 500m, and after 1000m the effects are similar to no treatment zones (Li et al. 2013).

The control groups are on the same road as this is the best solution regarding road conditions to camera treatment zones. As the observed roads are the main arterial links between different places in Estonia, thus there are no similar alternative roads for comparison. An alternative is to use the regional or national traffic trends, but these gave weaker odd ratios than selected comparison road sections.

For making before-and-after analysis, the Appendix 5 and Appendix 6 are compared. The results are presented in Table 7. The camera enforcement zone data Appendix 5 contains accidents (Acc), fatalities (Fat) and persons injured in accidents (Inj) on the observed roads. The accident data is available from its location on the road kilometer basis. The data is combined annually (from 2003 to 2017) to flatten seasonal, weather, day and night random fluctuations in accidents recommended by Hirst et al. (2004). The accident data is combined with the speed camera locations data by adding the speed camera location to accident data and selecting annual accidents before and after the speed camera in 1000m range.

The comparison group has built on similar principles as Appendix 6. It contains accidents (Acc), fatalities (Fat) and persons injured in accidents (Inj) on the observed roads. The comparison road is selected so that between the speed camera enforcement zone and comparison sections is at least 2000 m buffer zone for eliminating any spillover effects. The selected road type and traffic flows are similar to speed camera zones. Mostly the four-lane highways are excluded from comparison group because of the very different road characteristics.

Table 7: The results of the before-and-after analysis with the comparison group.

Roads		KPI after	tA in years	KPI before	tB in years	Naive BA of Cams	Control group road trend BA	AR(%) - camera net effect with trend removed	KPI_E - expected accidents	ESC - camera effects in numbers	Odd ratio (OR) with the control group
Tallinn-Tartu-Võru-Luhamaa	Acc	56	7	118	8	-45.8%	-44.2%	-1.5%	58	-2	1.01
	Fat	2	7	25	8	-90.9%	-40.6%	-50.3%	13	-11	
	Inj	100	7	231	8	-50.5%	-38.7%	-11.8%	124	-24	
Tallinn-Pärnu-Ikla	Acc	33	7	61	8	-38.2%	-36.7%	-1.4%	34	-1	0.99
	Fat	5	7	14	8	-59.2%	-40.7%	-18.4%	7	-2	
	Inj	59	7	83	8	-18.8%	-53.4%	34.6%	34	25	
Tallinn-Narva	Acc	18	5	87	10	-58.6%	-40.3%	-18.3%	26	-8	1.36
	Fat	2	5	20	10	-80.0%	-30.9%	-49.1%	7	-5	
	Inj	36	5	130	10	-44.6%	-37.4%	-7.2%	41	-5	
Ääsmäe-Haapsalu-Rohuküla	Acc	4	4	17	11	-35.3%	-11.9%	-23.4%	5	-1	1.08
	Fat	0	4	7	11	-100.0%	-51.5%	-48.5%	1	-1	
	Inj	4	4	29	11	-62.1%	-3.8%	-58.3%	10	-6	
Saku-Laagri	Acc	2	4	3	11	83.3%	175.0%	-91.7%	3	-1	0.60
	Fat	0	4	0	11	0.0%	0.0%	0.0%	0	0	
	Inj	2	4	4	11	37.5%	175.0%	-137.5%	4	-2	
Tallinn-Rannamõisa-Kloogaranna	Acc	6	4	23	11	-28.3%	-14.1%	-14.2%	7	-1	1.01
	Fat	1	4	4	11	-31.3%	37.5%	-68.8%	6	-5	
	Inj	7	4	25	11	-23.0%	-21.9%	-1.1%	7	0	
Tallinn-Rapla-Türi	Acc	3	4	30	11	-72.5%	-27.1%	-45.4%	8	-5	1.98
	Fat	0	4	8	11	-100.0%	-78.8%	-21.2%	0	0	
	Inj	4	4	61	11	-82.0%	-19.2%	-62.8%	18	-14	
Tallinn-Paldiski	Acc	2	2	35	13	-62.9%	-41.4%	-21.4%	3	-1	1.04
	Fat	0	2	4	13	-100.0%	-67.5%	-32.5%	1	-1	
	Inj	2	2	38	13	-65.8%	-53.6%	-12.2%	3	-1	
Totals (T) Average (A) Means	Acc	124	5	374	10	-42.0%	-31.9%	-19.9%		-20	1.03
	Fat	10	5	82	10	-85.4%	-40.7%	-40.5%		-25	
	Inj	214	5	601	10	-47.6%	-29.6%	-12.0%		-26	
		T	A	T	A	Mean	Mean	Mean		T	Mean

Source: Police and Border Guard Board (2018), compiled by the author.

The comparison results in Table 7 are combined over the road speed camera sections as the aim is to find the cumulative effects of all speed cameras together. It is possible to look at the performance of individual cameras, but this work goes out of the scope of this thesis. The results table contains accidents (Acc), fatalities (Fat) and persons injured in accidents (Inj) on the observed roads. The comparison is built up by observing accidents, fatalities and injured numbers before (tB) and after a period (tA) in years. The first result is a naïve before-and-after comparison (Naïve BA of cams) that usually overestimates the real effects of speed cameras (Hirst et al. 2004; Persaud et al. 2007).

The overall traffic safety trend or effects of other measures implemented has not disaggregated from the results. The second result (control group road trend) is the overall trend effect or the effects of other traffic safety measures implemented. The third is the net effects of the observed speed camera sections. The section of expected accidents will show what would have been the accident, fatalities of injured rate if the speed cameras would not have implemented. The camera effects in numbers show the effect in numbers calculated by using Equation 6. The odds ratio is calculated by using Equation 3 and shows the comparability of the observed camera sections and the comparison group. The most results are in the range of 95% confidence level, and the mean result is 1.03. We can be confident that the road sections of comparison group are good enough to estimate the trend effect accurately.

By removing the trend with comparison group the combined results are following: the overall accident numbers are reduced in median by 19.8% or by 20 accidents. The reduction is similar (19%) to Jones et al. (2008) with 29 mobile camera network and Goldenbeld and van Schagen (2005) results (21%) with 28 mixed cameras network. Later used similar observation method, the BA with an experimental (targeted speed enforcement) and a comparison (no targeted speed enforcement) condition. Gains et al. (2004) with the observation of 2300 cameras in 23 sites got a crash reduction of 22% and used simple BA method and EB for removing the RTM. Other author’s results, in the literature review, are on average 10% higher or lower.

The number of fatalities has fallen in median by 40.51% or by 25 in numbers and is near the result (44%) of the Jones et al. (2008). Shin et al. (2009) with six static cameras network had slightly higher fatalities reduction (46-56%) and also used the BA method with comparison groups. Other author’s results with different methods in the literature review are on average twice as low.

The injured rate has fallen in median by 12% and by 26 in numbers over the combined observation period ranging from two to seven years. The comparable result (11%) were only by Mountain et al. (2004) with 62 static cameras system which used EB method. Other authors got approximately 10-15% higher injuries reduction rates.

5.3 Monetization of the inputs

The cost of a prevention program is the building and management of a camera network, the procurement and management of a written warning information system and the cost of the processors' work. The cost of the speed cameras program can be found by adding the costs of infrastructure, software, and Police (Equation 8). The total cost of speed camera infrastructure is 4 083 260 euros (see Appendix 1). The total cost of the written warning information system is 645 495 euros, including the software component of 547 442 euros (see Appendix 2).

The Police work payments costs are illustrated in Table 8, and is calculated by publicized public sector payroll data (Ministry of Finance, 2018) (see Appendix 3), the office and the equipment costs are calculated by using the workplace and equipment cost from data chapter 4.4. The cumulative total control costs are summed up from 2011 to 2017. The total cost of maintaining the written warning procedure since it started is 4 381 252 euros.

Table 8: The annual control cost of written warning procedure.

	2017	**2016**	**2015**	**2014**	**2013**	**2012**	**2011**
Payroll	262 971	255 312	223 029	215 445	208 118	201 041	194 204
Workplace	438 867	426 084	413 301	400 902	388 875	377 209	365 893
Equipment			5 000				5 000
Totals	**701 838**	**681 396**	**641 331**	**616 347**	**596 993**	**578 250**	**565 097**

Sources: The Ministry of Finance (2017) and ERA (2018), compiled by the author.

When converting inputs to money, we use the cost of crashes, accidents, fatalities and injured (Table 4 and Table 5) and multiply it with the effects from the results of Table 7. As the camera programme is a running project and cameras are installed at different times, all the effects and periods are road based, but the results are summed up as the new camera sections are implemented. The primary interest is the total effect of the current program not on the individual roads.

Table 4 illustrates the costs of fatalities, injuries, and accidents. As the values were calculated in 2005 by Koppel, the costs have obviously changed in 2017. For this reason the previous costs of fatalities, injuries and accidents are updated by using the annual growth of SKP. The previous costs calculated by Koppel (2005) are hypothetical as this cost will not always realize accurately. On the other hand, the costs of Estonian Traffic Insurance Fund (ETIF) are more direct (Table 5). This is the actual money spent for compensating the consequences of accidents. When comparing the overall accident data (Table 3) with the results of ETIF data

(Table 5), we can see that the combined accident rate with Police involvement account is on average 15.44% and 14.65% in the median of all traffic-related insurance cases. The crashes share 10.78% on average and 10.23% in the median.

When monetizing the KPI-s, using Equation 10, the results of combined periods of the observed roads are in Table 9.

Table 9: The cost of accident, fatalities, and injuries by ETIF and Koppel (2005).

Roads		**tA/years**	**Camera effects in numbers (ESC)**	**The average cost of insurance**	**Average averted societal cost of Koppel**	**Insurance cost according to ETIFF**	**Averted societal costs according to Koppel (2005)**
Tallinn-Tartu-Võru-Luhamaa	Acc	7	-2	1 448	14 570	2 317	23 312
	Fat	7	-11	61 759	1 117 833	679 349	12 296 163
	Inj	7	-24	4 154	21 249	98 881	505 810
Tallinn-Pärnu-Ikla	Acc	7	-1	1 448	14 570	1 112	11 188
	Fat	7	-2	61 759	1 117 833	139 530	2 525 475
	Inj	7	25	4 154	21 249	-104 406	-534 068
Tallinn-Narva	Acc	5	-8	1 492	15 488	11 898	123 514
	Fat	5	-5	65 650	1 188 269	322 282	5 833 321
	Inj	5	-5	4 042	22 588	19 013	106 251
Ääsmäe-Haapsalu-Rohuküla	Acc	4	-1	1 528	15 836	2 210	22 908
	Fat	4	-1	67 122	1 214 901	82 915	1 500 760
	Inj	4	-6	4 052	23 094	24 920	142 028
Saku-Laagri	Acc	4	-1	1 528	15 836	1 528	15 836
	Fat	4	0	67 122	1 214 901	0	0
	Inj	4	-2	4 052	23 094	8 104	46 188
Tallinn-Rannamõisa-Kloogaranna	Acc	4	-1	1 528	15 836	1 815	18 805
	Fat	4	-5	67 122	1 214 901	335 610	6 074 505
	Inj	4	0	4 052	23 094	414	2 362
Tallinn-Rapla-Türi	Acc	4	-5	1 528	15 836	7 571	78 460
	Fat	4	0	67 122	1 214 901	0	0
	Inj	4	-14	4 052	23 094	56 415	321 530
Tallinn-Paldiski	Acc	2	-1	1 579	16 674	1 821	19 228
	Fat	2	-1	69 449	1 257 020	69 449	1 257 020
	Inj	2	-1	3 694	24 317	2 639	17 369
Totals (T), Averages (A), Means (M)	Acc	5	-20	1 510	15 581	30 271	313 251
	Fat	5	-25	65 888	1 192 570	1 629 135	29 487 243
	Inj	5	-26	4 032	22 722	105 980	607 471
		A	**Total**	**Average**	**Average**	**1 765 387**	**30 407 965**

Source: ETIF (2018) and Koppel (2005), compiled by the author.

In total, the 20 avoided accidents could have saved 313 251 euros, the 25 avoided fatalities could have saved 29 487 243 euros, and the 26 avoided severe accidents could have saved 607 471 euros from the start of the speed camera program. Unfortunately, there are no detailed data available about the minor crashes on the roads observed, and thus the cost of these should be measured in future research. In this thesis, we can give some rough estimates about these costs by assuming that the observed relationship (Table 1) between minor crashes and accidents with at least one injured is on average 2.18. It gives us a rough estimation that 57 minor crashes could have been avoided, and the savings for society could be 26 multiplied with 2.18 multiplied with 1510 euros equals 85 587 euros for the period. If we compare this with the overall insurance cases statistics, then the number could be ten times higher as the relationship between the crashes and overall insurance cases is 10.78% on average. Unfortunately, there is not this type of data available on observed period, and thus it is not presented.

Table 9 is composed by taking the period of the implemented speed camera section and taking the average cost of accidents, fatalities, and injuries by the same period from Tables 4 and 5, and multiplying it with the combined effects of observed road sections.

Table 10: The number of camera measurement cabins and the cost of speed cameras in euros.

Observed road	Number of camera measurement cabins	The cost of speed cameras in euros
Tallinn-Narva	11	1 473 678
Tallinn-Tartu-Võru-Luhamaa	24	3 215 297
Tallinn-Pärnu-Ikla	11	1 473 678
Ääsmäe-Haapsalu-Rohuküla	4	535 883
Saku-Laagri	1	133 971
Tallinn-Rannamõisa-Kloogaranna	4	535 883
Tallinn-Rapla-Türi	5	669 853
Tallinn-Paldiski	4	535 883
Total	**64**	**8 574 124**

Source: ERA (2018)[6], compiled by the author.

The total cost of the prevention program is currently 9 110 007 euros by using Equation 7. The cost per speed camera measurement cabin can found by dividing the total cost by the top-

[6] Camera Locations: https://www.mnt.ee/eng/roads/cameras-speed-limit-enforcement/camera-locations

down method with the number of measuring points. 9 110 007 euros divided by 68 equals 133 971 euros. As 64 measuring cabins are located on the roads under observation, the cost of speed cameras is divided between the number of camera measurement cabins and costs are in Table 10. The cost of the speed camera network under observation is 8 574 124 euros.

5.4 The desired effects

To meet the target set by the Traffic Safety Program 2016 - 2025, the number of fatalities in traffic accidents has to reduced fewer than 40 per year, and the injured has to reduce on the average of three consequential years less than 330. The Table 11 illustrates the relationship in percentage between the overall national traffic accidents (NAcc), fatalities (NFat) and injured (NInj) to the observed roads traffic accidents (ObRAcc), fatalities (ObRFat) and injured (ObRInj). The KPI ratios of the roads under observation are on average, 11.43% (median 11.68%) on accidents, 26.54% (27.08% median) for fatalities and on 13.61% (median 13.95%) on injured.

When looking the general traffic safety trend with fatalities, we can see that the number has dropped from an average of 145 on before 2011 to on average 74 after 2011 and the drop is 71. When we compare it with the average share of the observed roads 26.54% on fatalities, then we see the estimate is 19 saved lives.

When we compare the median levels of 167 before 2011 and 77 after 2011 we get the difference of 90 lives and the median share is 27.08% and thus the treatment effect is 24 saved lives. It is almost similar to measurements in Table 11 (25 lives saved).

When we compare the general traffic safety trend with injuries we can see that the number has dropped from an average of 2512 on before the period of 2003 to 2011 to on average 1758 of them after a period from 2011 to 2017 and the drop is 754. When we compare it with the average share of the observed roads, 13.61% we see the estimated share should be is 103 less injured. The measured combined effect was 26. By looking at the historical data, we can see that the accident and injuries rates have been settled down to relatively stabilized levels since 2008 to 2017. Thus the expected speed camera system effects for preventing accidents and injuries should be expectedly low. However, when looking the reduction of fatalities, we can assume that the effect could be enough to prevent fatalities.

Table 11: The accidents, fatalities, and injuries on the observed roads and the ratio in percentage from national accidents, fatalities and injuries statistics before and after the speed camera program deployment.

Roads		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
ObRAcc	Acc	162	257	328	379	342	226	151	139	153	154	129	123	113	179	151
ObRFat	Fat	38	41	55	67	50	22	14	31	24	26	22	14	19	15	13
ObRInj	Inj	240	428	464	575	488	339	218	204	222	253	209	175	196	255	241
NAcc	Acc	1675	2201	2340	2585	2442	1851	1193	1177	1475	1377	1373	1425	1374	1462	1407
NFat	Fat	131	167	171	206	197	125	85	76	92	84	79	77	67	71	48
NInj	Inj	2184	2811	3029	3515	3254	2357	1482	1466	1880	1704	1704	1732	1719	1842	1727
ObR/N(Acc)	Acc	9.7%	11.7%	14.0%	14.7%	14.0%	12.2%	12.7%	11.8%	10.4%	11.2%	9.4%	8.6%	8.2%	12.2%	10.7%
ObR/N(Fat)	Fat	29.0%	24.6%	32.2%	32.5%	25.4%	17.6%	16.5%	40.8%	26.1%	31.0%	27.8%	18.2%	28.4%	21.1%	27.1%
ObR/N(Inj)	Inj	11.0%	15.2%	15.3%	16.4%	15.0%	14.4%	14.7%	13.9%	11.8%	14.8%	12.3%	10.1%	11.4%	13.8%	14.0%

Source: Police and Border Guard Board (2018), compiled by the author.

5.5 Comparison of inputs with impacts and conclusions on cost-effectiveness

For finding the cost-effectiveness of the speed camera program, the corresponding cost of the camera program must be summed up over the years before-and-after the analysis and compared on average and by the end of the year with the number of accidents, fatalities, and injuries. The KPI ratios of the roads under observation are on average, 11.43% (median 11.68%) on accidents (20), 26.54% (27.08% median) for fatalities (25) and on 13.61% (median 13.95%) on injured (26) when compared to the national levels.

Cost-effectiveness (CE) is found by dividing the total cost of the program with the avoidable accidents which included the fatalities or at least one seriously injuries person over the full program period. In this case, the CE has limited application. The deaths and injuries are direct consequences of the accident. We have to combine these all together and then we can present it as the reduction of a serious accident that would have also caused on average 1.3 fatalities and 1.25 injured persons.

$$CE = \frac{8\,574\,124 \text{ euros}}{20 \text{ accidents}} = 428\,706 \text{ euros}$$

CE can be used to compare the effectiveness of the alternative programs to find the most effective way to avoid the one severe accident with on average of 1.25 fatalities and 1.3 injured persons (Chisholm 2000; Welsh, Farrington 2000; McIntosh, Li 2012).

The interest of society is the reduction of the fatalities and injured influenced by the program. In this context, the average decrease in the number of fatalities and injuries on the roads equipped with speed cameras has been higher than it could be according to the BA study (see Table 7). Several other factors such as driver risk behavior, road conditions, road construction, traffic Police supervision, and then static speed cameras on hazardous sections play a role in road safety (Elvik, 1997; Mountain et al. 2004; Hirst et al. 2004). We can identify the increased safety of roads under the overall road safety trend. As prevention is the primary focus of the road safety program, the combination of all measures must increase overall road safety. The benefits of road sections surveyed in the study have decreased the number of fatalities and injuries before and after the implementation of the speed camera program, which is characterized by Table 7.

5.6 Calculating the benefit-cost ratio and making the conclusions to society

During the effectiveness analysis in Table 7, the impact of the speed camera program could be less than 20 accidents, 25 fatalities, 26 injured and 57 crashes. The speed cameras were introduced at different times, and the analysis has been done through the whole deployment period. In order to calculate the BCR, the combined costs of KPIs must be divided into the corresponding investments in Table 8 using the Equation 8.

When we look only the avoidable insurance data from Table 9, and we do not introduce the revenue, we get the benefit-cost ratio 1 (BCR_1). The serious accidents and minor crashes are combined and multiplied by the average cost of car insurance case. There is no differentiation in accident seriousness by the available data. The 77 accidents multiplied with the 1510 euros equals a 116 270 euros. The total cost of 26 seriously injured persons for insurance is 105 980 euros. The total cost of 25 fatalities for insurance is 1 629 135 euros. By using Equation 9, from chapter 3.3, the benefit-cost ratio is shown in BCR_1.

$$BCR_1 = \frac{116\ 270 + 105\ 980 + 1\ 629\ 135}{8\ 574\ 124} = 0.21$$

In the direct costs approach results (BCR_1) the program is using more resources then it should help to save. If we introduce the revenues of written warning procedure from Table 6, then we add an additional amount of 9 551 827 euros, and the result is shown in BCR_2.

$$BCR_2 = \frac{113\ 071 + 101\ 443 + 1\ 543\ 974 + 9\ 551\ 827}{8\ 574\ 124} = 1.32$$

We can see that the revenue covers all the expenses of the speed camera program and adds additional 977 703 euros to state revenues. All the studies observed in literature review did not include the revenue analysis. We can see that the minimal direct net benefit for society is at least 0.32 euros with the corresponding one euro investment.

For calculating the BCR by using the averted societal costs of Koppel (2005) from Table 9, the calculated benefit to society is 313 251 euros per 20 accidents, 29 487 243 euros per 25 fatalities, 607 471 euros per 26 injured persons and 86 070 euros per 57 minor crashes. The combined benefit for society is 30 407 965 euros. The benefit-cost ratio 3 is shown in BCR_3.

$$BCR_3 = \frac{313\ 251 + 29\ 487\ 243 + 607\ 471 + 86\ 070}{8\ 574\ 124} = 3.55$$

The BCR_3 without the written warning revenue is 3.55. In this case, the society saves extra 2.55 euros per every euro invested into the speed camera program. When we introduce the revenues of written warning procedure, we get following results in BCR_4.

$$BCR_4 = \frac{309\,760 + 29\,706\,725 + 587\,288 + 84\,567 + 9\,551\,827}{8\,574\,124} = 4.66$$

The combined hypothetical net benefits are up to 3.66 euros per every euro invested. 4.66 is near the result (1:5) of the Hess and Polak (2007).

For taking into account the regression-to-mean effect (RTM) for BCR_2 and BCR_4. We expect it to be 10% as described by Goldenbeld and van Schagen (2005). In this case, we subtract 10% from the combined results of Averted Societal costs and get the new results:

$$BCR_{2-RTM} = \frac{(1\,765\,387 \times 0{,}9) + 9\,551\,827}{8\,574\,124} = 1.30$$

$$BCR_{4-RTM} = \frac{(30\,407\,965 \times 0{,}9) + 9\,551\,827}{8\,574\,124} = 4.31$$

As we can see, the BCR did not change much. However, when the RTM effect is greater, then it can affect the calculation considerably and can mislead to allocate funds to further investments in road safety programs that are not as beneficial as presented.

Although the number of accidents and injured people in traffic increased over the last four years, the number of cars and traffic volume has also increased, according to the ERA. At the same time, the number of people killed in traffic has fallen far more than according to general statistical trends could be expected.

The first limitation of this thesis is that the RTM effect is not calculated separately. The primary reason for this is the lack of data to make proper road accident model for Empirical Bayesian analysis. Thus this thesis should be further developed by evaluating the safety effects with more recent and technologically advanced models for simulating the future accident rates.

The second limitation is that the net present value of the road safety investments for every camera installment is not calculated. The reason for this is also the lack of data, as the details of the contracts are treated as business secrets and are protected by the law. The only public data available is through an electronic procurements registry (for more details look Appendix 1).

The third limitation is the available data quality. The current ERA, ETIF, PBGB statistics do not differentiate the seriousness of the injuries. Therefore it is not possible to calculate how many persons will recover fully from the accidents and how many will have permanent incapability after the accident. This has some extra future research opportunity to differentiate the seriousness of accidents by combining the accident data with the data from the Estonian Health Insurance Fund.

The current speed camera network is using well studied and proven the older technology. The effective range of fixed speed cameras are around 500m (Li et al. 2013). This is a very limited range of treatment effect. There are newer technical solutions available like average speed enforcement. Several studies have observed the effects of average speed enforcement, and the results are better in average speed compliance, public acceptance, and prevention of accident or fatalities rates (Soole et al. 2013). Estonian Road Administration should consider upgrading the current speed camera technology to average speed enforcement as some of the infrastructures can be reused when the current cameras will depreciate.

Estonia is a small country and the traffic flows, and accident rates are relatively small. However, the observed results are similar to several studies using similar approaches (Gains et al. 2004; Mountain et al. 2004; Jones et al. 2008; Shin et al. 2009). The main caution of the estimates of this work is the possible regression-to-mean effect. By looking at the literature, it has been noted that the more extended datasets should diminish the randomness of accidents and thus the regression-to-mean (RTM) effect should be insignificant. Some researchers have postulated that within five year observation period will have RTM effect in a range of 5-10% (Goldenbeld, van Schagen 2005). For this thesis, the dataset is 15 years long, and thus we can argue confidently that the RTM effect is also in 5-10% range. If the RTM is in range of 10% the BCR is in range of 1.30 to 4.31 by using the corresponding calculations of BCR_3 and $BCR_{4.}$

The main implication of this thesis is that the current speed camera program investment on observed roads has positive impacts. First, it has a considerable effect on reducing the fatalities - 25 lives saved. Secondary, the speeders have paid more fines than the program costs. An extra 977 703 euros is added to state revenue. In that sense, the speed camera program is the road safety measure and the state revenue filler.

6. Conclusions

The aim of this thesis was to calculate the cost-effectiveness and benefit-cost ratio of the Estonian speed camera programme by combining the speed camera effectiveness methods with the crime prevention benefit-cost analysis methods.

The speed camera programs have been extensively studied in the scientific literature for over 30 years. The economic feasibility view of these works is missing or is a side product of some works (Hess and Polak, 2007; Shin et al. 2009; Newstead and Cameron, 2003; Gains et al. 2004). Only two speed camera effectiveness studies have been done in Estonia (Draba 2012; Äär 2014) but had no economic feasibility analysis. This thesis fills the economic feasibility analysis cap in Estonia's case.

This thesis analyses the data from the Estonian Road Administration, Police and Border Guard Board and Estonian Traffic Insurance Fund (ETIF). To find the speed camera effectiveness the before-and-after method with comparison group is used. To calculate the cost-effectiveness and benefit-cost ratios the crime prevention cost-effectiveness and benefit-cost analysis methods are used and combined with the costs data of ETIF and updated calculations of Koppel et al. 2005.

This thesis has similar results with several studies using similar approaches (Gains et al. 2004; Mountain et al. 2004; Jones et al. 2008; Shin et al. 2009). The main caution is the exact regression-to-mean effect that should be calculated in future research.

The cost-effectiveness shows that the cost of avoiding 20 accidents with the consequences of at least one 1.3 injured and 1.25 fatalities is about 428 706 euros. It can be used for auditing the current project and evaluate if there are more cost-effective ways to get similar or better results.

Consequently, we can argue that the speed camera program is beneficial for society because the benefit-cost ratio is > 1. By removing the trend and RTM effect, the BCR is 4.31. However, the revenues earned by the camera network are higher than the total cost of the program. Thus the investment by the society is paid up entirely by the speeders, and additional 977 703 euros is added to state revenue. Other benefits like 25 saved lives are basically supplementary.

This work has several future research opportunities like calculating the exact RTF effect, finding out the net present value of the current speed camera program investment and disaggregating the accident data so that the seriousness of the accidents can be separately calculated.

7. Appendixes

Appendix 1: Procurement costs of speed camera infrastructure

This table would contain the real costs of contracts if the procurement fulfilled. The data collected from national electronic procurement registry by using keywords “kiiruskaamera,” and the relevant results extracted from the search result. The results are procurements and costs of speed camera system.

Name of the procurement	Contract cost in euros
Kristiine kiiruskaamerate hooldus 2017-2018	32 376.00
Harjumaa Harku vald Muraste kiiruskaamerate liitumisühenduse ehitamine LP2394, LP2393	12 274.30
Statsionaarsete kiiruskaamerate ja mõõtekabiinide ost, paigaldus ja hooldus	361 441.77
Kiiruskaamerate hooldusteenus	879 935.00
Statsionaarsete kiiruskaamerate ost, paigaldus ja hooldus	295 202.44
Statsionaarsete kiiruskaamerate ja mõõtekabiinide ost, paigaldus ning hooldus	769 686.55
Kiiruskaamerate valveteenus	25 920.00
Järva maakonna kiiruskaamerate mõõtekabiinide hooldustööd 01.02.2012 kuni 31.12.2015	839.32
Statsionaarsete kiiruskaamerate ost, paigaldus ja hooldus	789 280.00
Kiiruskaamerate ümbertõstmise ja häirekõnedele reageerimise teenus	37 570.00
Kiiruskaamerate valveteenus	12 884.59
Statsionaarsete kiiruskaamerate ost ja paigaldus	865 850.09
Total cost	**4 083 260.06**

Source**:** Electronic procurement registry, compiled by the author.

Appendix 2: Procurement costs of the written warning information system

This table would contain the real costs of contracts if the procurement fulfilled. The data collected from national electronic procurement registry by using keywords "hoiatusmenetlus," and the relevant results extracted from the search result. The results are procurements and costs of written warning information system and its infrastructure.

Name of the software procurement	**Contract cost in euros**
Hoiatusmenetluse infosüsteem	75 614.77
Hoiatusmenetluse ja menetluse infosüsteemide vahelise liidese arendustööd	34 895.76
Hoiatusmenetluse infosüsteemi ja POLIS üldosa liidese arendustööd	10 302.56
Politsei- ja Piirivalveameti hoiatusmenetluse infosüsteemi tarkvara hooldus- ja arendustööde tellimine	26 629.81
Politsei- ja Piirivalveameti hoiatusmenetluse infosüsteemi tarkvara hooldus- ja jätkuarendustööde tellimine perioodiks 2015-2018.	400 000.00
Software total cost	**547 442.90**
Name of the hardware procurement	
Hoiatusmenetluse infosüsteemi kõrgkäideldava majutuskeskkonna loomiseks vajaliku riist- ja tarkvara hankimine	98 051.97
The total cost of written warning procedure information system	**645 494.87**

Source**:** The electronic procurement registry, compiled by the author.

Appendix 3: Salaries and jobs of the Police Offices

Annual salary and posts in the written warning procedure. The officials' names removed due to Estonian data protection law. The table contains job title and gross salaries in 2016. The total personnel cost for the employer (PBGB) is approximately 33% higher due to the state social tax.

Organization	Bureau	Position	Annual salary in euros
Plitsei- ja Piirivalveamet	liiklusmenetlusteenistus	vanemspetsialist	10 956,07
Plitsei- ja Piirivalveamet	liiklusmenetlusteenistus	vanemspetsialist	11 232,93
Plitsei- ja Piirivalveamet	liiklusmenetlusteenistus	liikluspolitseinik	12 435,94
Plitsei- ja Piirivalveamet	liiklusmenetlusteenistus	juhtivspetsialist	12 448,01
Plitsei- ja Piirivalveamet	liiklusmenetlusteenistus	juhtivspetsialist	12 471,59
Plitsei- ja Piirivalveamet	liiklusmenetlusteenistus	juhtivspetsialist	12 736,48
Plitsei- ja Piirivalveamet	liiklusmenetlusteenistus	liikluspolitseinik	14 330,84
Plitsei- ja Piirivalveamet	liiklusmenetlusteenistus	liikluspolitseinik	17 835,80
Plitsei- ja Piirivalveamet	liiklusmenetlusteenistus	liikluspolitseinik	18 243,91
Plitsei- ja Piirivalveamet	liiklusmenetlusteenistus	liikluspolitseinik	19 943,99
Plitsei- ja Piirivalveamet	liiklusmenetlusteenistus	teenistuse vanem	25 055,68

Source: Ministry of Finance (2018), compiled by the author.

Appendix 4: Traffic accidents with injuries or fatalities from 2003-2017

The accidents, fatalities, and injuries on observed roads from 2003 to 2017. The grey colour marks the years when speed cameras were installed.

Roads		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Tallinn-Tartu-Võru-Luhamaa	Acc	52	82	103	120	103	68	34	42	59	50	53	40	22	42	39
	Fat	8	13	14	22	17	5	6	6	10	7	4	3	4	1	0
	Inj	89	140	160	197	170	105	51	62	86	94	97	65	30	62	61
Tallinn-Pärnu-Ikla	Acc	27	42	53	51	57	35	24	21	23	24	21	20	25	39	24
	Fat	7	6	13	7	11	4	3	5	2	5	3	5	6	3	2
	Inj	56	78	73	71	91	44	41	29	30	32	27	22	41	61	44
Tallinn-Narva	Acc	43	57	99	116	91	48	41	45	35	37	24	30	36	52	44
	Fat	12	13	21	24	13	7	0	11	5	8	6	5	6	8	8
	Inj	51	90	132	169	141	93	57	65	51	57	38	49	79	73	72
Ääsmäe-Haapsalu-Rohuküla	Acc	11	19	16	18	16	16	9	7	12	5	5	10	1	12	17
	Fat	3	0	1	3	1	3	4	4	1	0	4	0	0	1	2
	Inj	12	27	20	35	24	19	8	13	17	10	6	12	2	14	28
Saku-Laagri	Acc	1	3	4	3	4	8	2	3	1	4	1	1	3	5	1
	Fat	0	0	1	1	0	0	0	1	0	1	0	0	1	1	0
	Inj	1	9	4	2	5	14	3	3	1	6	1	1	3	4	1
Tallinn-Rannamõisa-Kloogaranna	Acc	4	5	7	20	16	11	15	4	5	9	6	10	4	9	10
	Fat	0	1	1	3	0	1	0	0	1	1	0	1	1	0	0
	Inj	4	4	7	23	20	15	17	7	6	13	11	9	4	13	14
Tallinn-Rapla-Türi	Acc	16	28	29	28	28	20	15	11	11	13	5	6	12	13	9
	Fat	7	5	3	4	2	1	0	1	3	2	1	0	0	0	1
	Inj	17	48	42	52	1	25	26	19	20	25	9	8	23	21	12
Tallinn-Paldiski	Acc	8	21	17	23	27	20	11	6	7	12	14	6	10	7	7
	Fat	1	3	1	3	6	1	1	3	2	2	4	0	1	1	0
	Inj	10	32	26	26	36	24	15	6	11	16	20	9	14	7	9

Source: Police and Border Guard Board (2018), compiled by the author.

Appendix 5: Traffic accidents with injuries or fatalities from 2003-2017

The traffic accidents, fatalities and injuries in the 1000 m range of the speed cameras. The grey colour marks the years when speed cameras were installed.

Roads		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Tallinn-Tartu-Võru-Luhamaa	Acc	10	14	25	27	17	8	6	11	12	12	7	7	2	10	6
	Fat	1	4	3	9	2	2	0	4	0	1	0	0	0	1	0
	Inj	19	25	52	61	34	12	11	17	17	30	7	12	7	18	9
Tallinn-Pärnu-Ikla	Acc	2	6	13	9	14	9	5	3	2	7	7	1	7	3	6
	Fat	1	1	3	2	3	1	1	2	1	1	1	0	2	0	0
	Inj	3	16	11	13	18	13	5	4	1	11	6	4	18	7	12
Tallinn-Narva	Acc	10	5	13	13	14	10	8	7	4	3	2	6	4	1	5
	Fat	1	2	2	4	5	0	0	5	0	1	1	1	0	0	0
	Inj	14	7	19	20	15	26	11	9	4	5	5	12	10	1	8
Ääsmäe-Haapsalu-Rohuküla	Acc	3	0	1	2	2	1	2	3	1	2	0	0	0	3	1
	Fat	1	0	0	1	0	0	2	3	0	0	0	0	0	0	0
	Inj	3	0	1	4	7	1	1	8	2	2	0	0	0	3	1
Saku-Laagri	Acc	0	0	0	0	1	1	0	0	1	0	0	0	1	1	0
	Fat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Inj	0	0	0	0	2	1	0	0	1	0	0	0	1	1	0
Tallinn-Rannamõisa-Kloogaranna	Acc	1	1	0	2	3	5	5	0	2	3	1	2	2	1	1
	Fat	0	0	0	2	0	1	0	0	1	0	0	0	1	0	0
	Inj	1	1	0	4	5	4	5	0	1	3	1	2	2	1	2
Tallinn-Rapla-Türi	Acc	1	2	3	5	4	4	3	1	3	2	2	0	0	2	1
	Fat	1	2	1	3	0	1	0	0	0	0	0	0	0	0	0
	Inj	0	2	3	10	8	6	8	1	10	7	6	0	0	3	1
Tallinn-Paldiski	Acc	2	4	2	4	6	4	4	1	1	4	3	0	0	1	1
	Fat	0	0	0	1	1	0	1	0	0	0	1	0	0	0	0
	Inj	2	4	2	3	8	4	4	1	1	6	3	0	0	1	1

Source: Police and Border Guard Board (2018), compiled by the author.

Appendix 6: The data and calculations of observed roads

Traffic accidents, fatalities and injuries in a comparison group of road sections without speed camera installment before and after deployment of speed camera program from 2003 to 2017. The grey colour marks the years when speed cameras were installed.

Roads		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Tallinn-Tartu-Võru-Luhamaa	Acc	29	43	46	54	49	42	13	19	19	29	30	22	10	24	10
	Fat	3	3	4	5	5	3	1	1	2	6	2	2	1	0	0
	Inj	48	70	64	83	84	66	18	26	33	47	59	30	10	32	35
Tallinn-Pärnu-Ikla	Acc	18	27	24	28	28	16	13	14	13	13	7	11	15	23	11
	Fat	5	3	7	2	7	0	0	3	1	3	0	2	4	2	2
	Inj	45	52	42	41	51	24	25	19	16	16	10	12	17	32	19
Tallinn-Narva	Acc	24	30	48	58	39	19	13	18	12	17	15	15	9	26	18
	Fat	9	8	9	10	5	2	0	3	4	5	4	4	3	2	6
	Inj	28	44	65	85	68	36	15	24	19	28	24	18	12	42	33
Ääsmäe-Haapsalu-Rohuküla	Acc	8	11	15	16	13	15	6	4	8	2	5	10	1	8	14
	Fat	2	0	1	2	1	3	2	1	1	0	4	0	0	1	2
	Inj	9	19	19	31	15	18	6	5	9	3	6	12	2	10	25
Saku-Laagri	Acc	1	3	4	3	2	7	2	2	0	1	1	1	1	3	1
	Fat	0	0	1	1	0	0	0	1	0	0	0	0	1	1	0
	Inj	1	9	4	2	2	13	3	2	0	1	1	1	0	2	1
Tallinn-Rannamõisa-Kloogaranna	Acc	2	3	5	13	11	6	8	4	3	6	3	6	2	7	5
	Fat	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0
	Inj	2	2	6	15	13	11	10	7	5	10	7	5	2	10	8
Tallinn-Rapla-Türi	Acc	12	17	18	18	20	13	7	9	7	10	2	6	11	11	8
	Fat	4	1	1	1	2	0	0	1	2	1	0	0	0	0	1
	Inj	8	30	28	31	28	15	9	16	10	18	2	8	22	18	11
Tallinn-Paldiski	Acc	3	14	9	17	15	10	4	5	5	7	9	3	10	4	6
	Fat	0	1	1	2	5	1	0	3	1	2	3	0	1	1	0
	Inj	5	20	16	21	21	12	5	5	8	9	14	4	14	3	8

Source: Police and Border Guard Board (2018), compiled by the author.

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